Demonstration of Deployment Accuracy of the Starshade Inner Disk Subsystem

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Outline

1. Introduction
   - Background
   - Objective
2. Experimental Apparatus
   - IDS Prototype
   - Gravity Compensation
   - Metrology
3. Experimental Procedures
   - Shimming
   - Deployment
4. Test Results
   - Data processing
   - Deployment Repeatability
   - Deployment Accuracy
5. Conclusions

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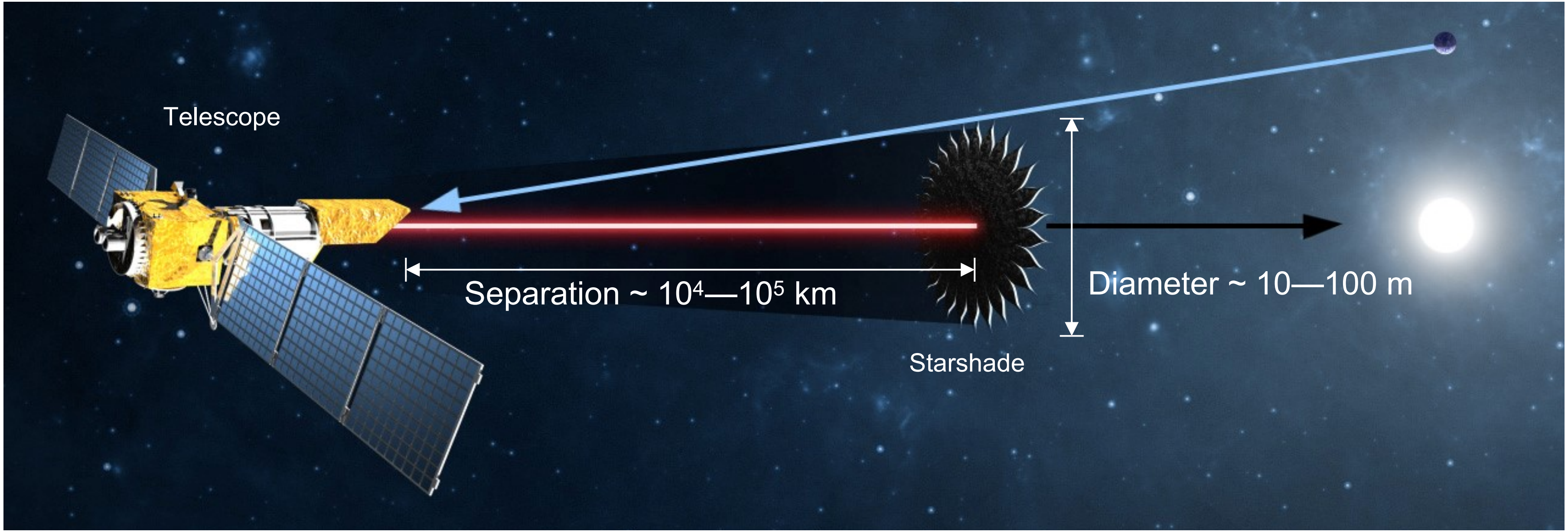
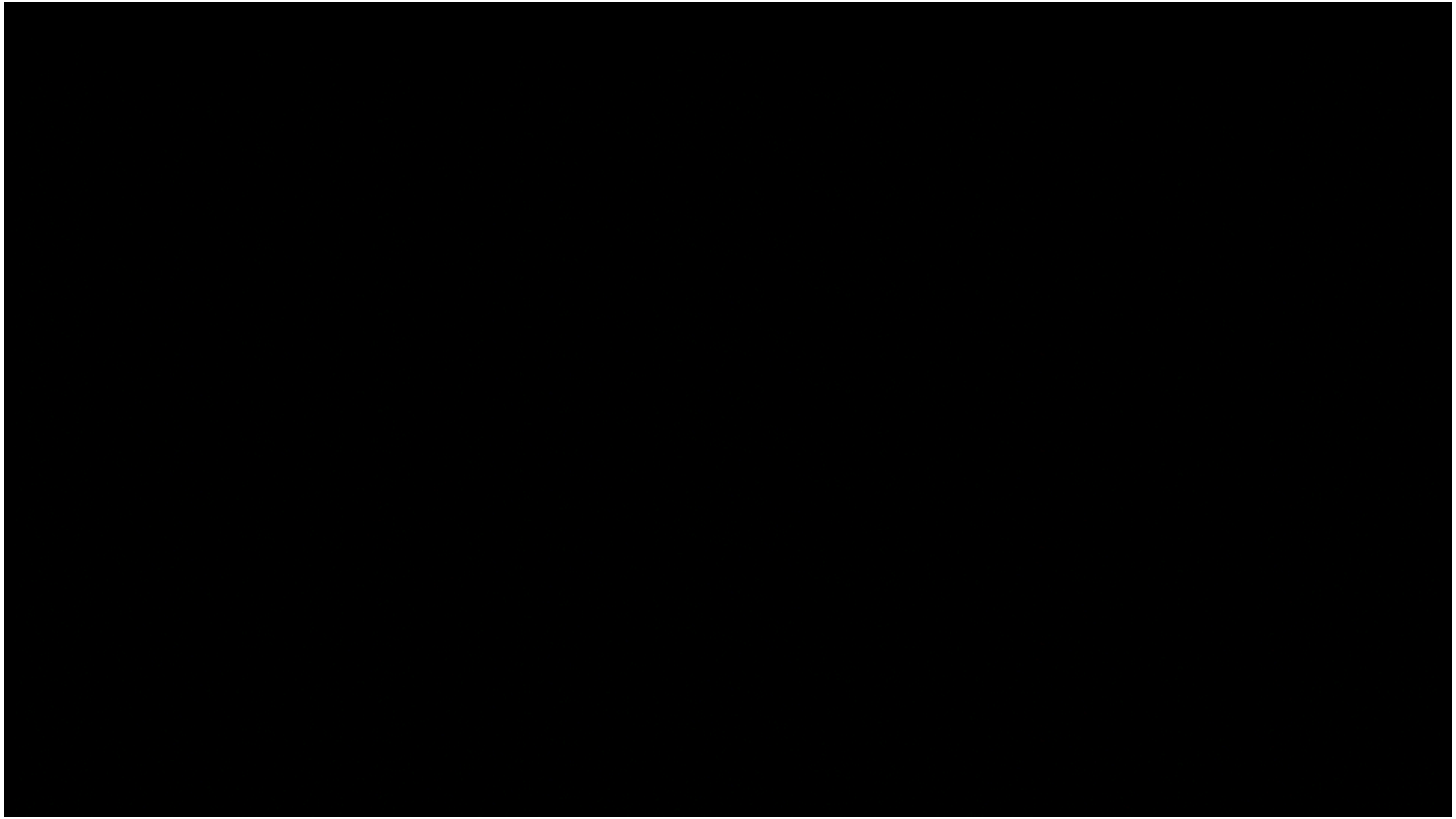
Introduction: Starshade

- Starlight suppression for exoplanet imaging using an external occulter
    - Independent spacecraft, formation flying with a space telescope
    - Desired starshade diameters ~ 10s of meters ⇒ deployable system

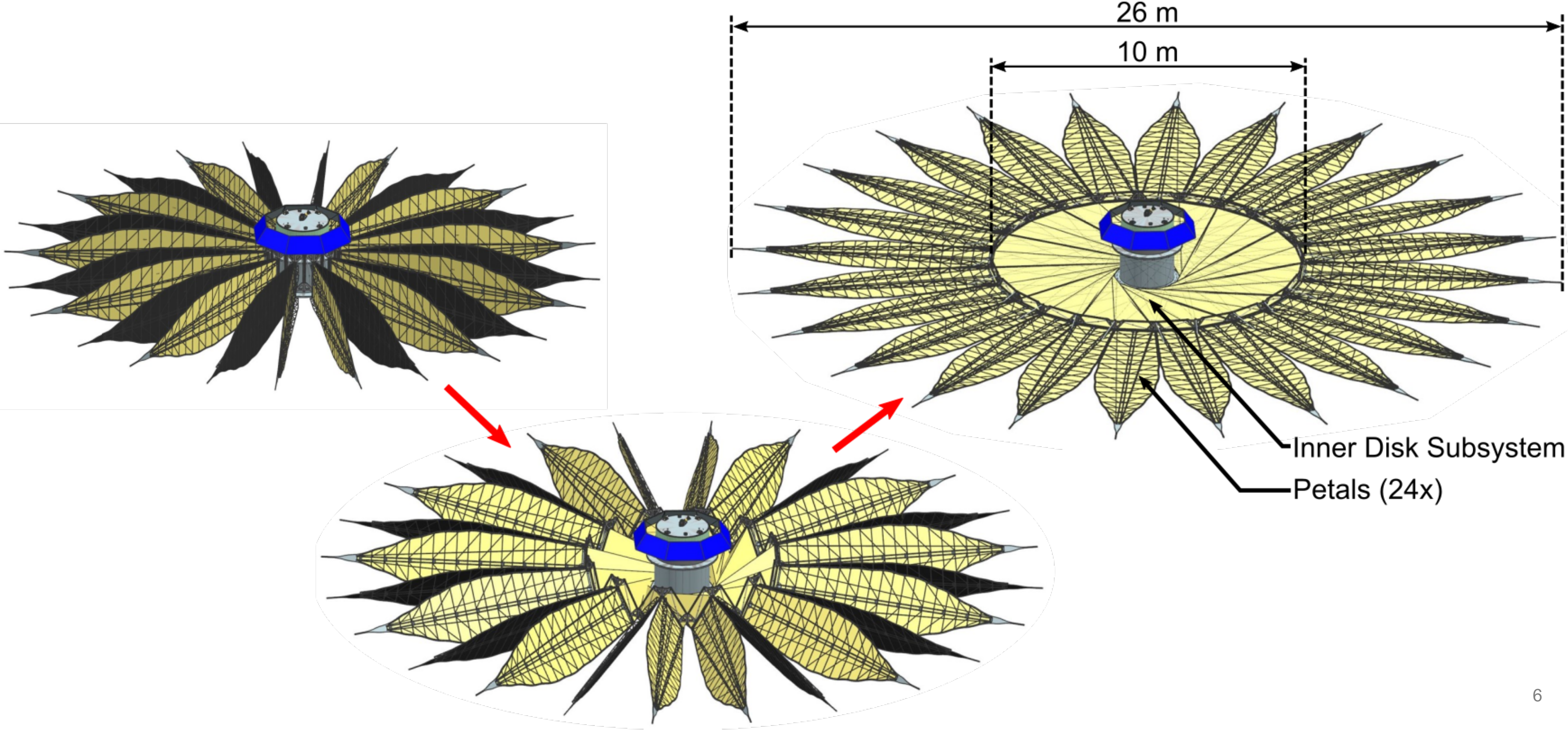


Starshade Deployment Concept



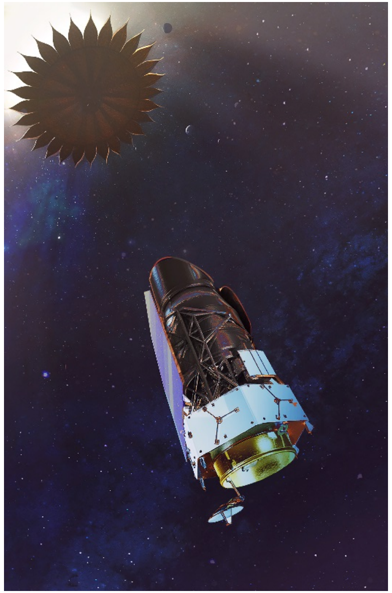
https://exoplanets.nasa.gov/resources/1015/flower-power-nasa-reveals-spring-starshade-animation/

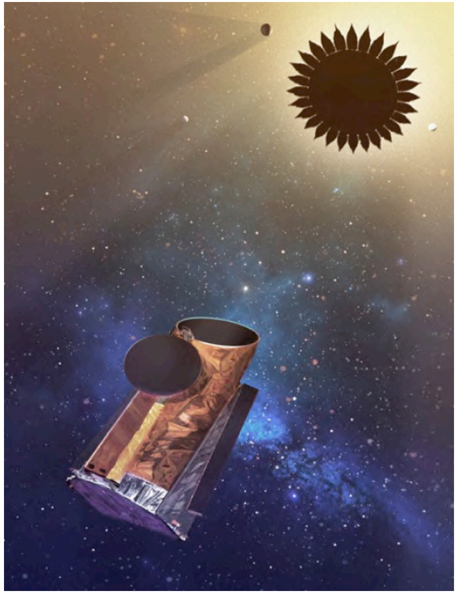
Starshade Inner Disk Unfolding Concept



Reference Mission Concepts for Starshade Technology

- WFIRST Rendezvous Probe concept – Starshade Rendezvous Mission (SRM):
  - Telescope diameter: 2.4 m
  - Separation: 26,000 km
  - Starshade: 26 m diameter, 8 m-long petals, 10 m-diameter inner disk
- Habitable Exoplanet Observatory (HabEx) concept starshade:
  - Telescope diameter: 4 m
  - Separation: 76,600 km
  - 52 m diameter, 16 m-long petals, 20 m-diameter inner disk
- This work is relevant to SRM at full-scale and to HabEx at half-scale





Background

- S5 (Starshade-to-TRL 5) activity within NASA's Exoplanet Exploration Program will bring starshade technology to Technology Readiness Level 5 (TRL5)
- Technology milestones across three areas:
    1. Optical testing and modeling of starlight suppression
    2. Formation flying between a space telescope and a starshade
    3. Stable and accurate deployable mechanical system
- Activities are underway to address these milestones
- We address Milestone 7C, related to the mechanical deployment accuracy of the starshade Inner Disk Subsystem (IDS)

Objective

- Address Milestone 7C of S5 Technology Development Plan through the repeated deployment and measurement of a full-scale IDS prototype

- Milestone 7C: Inner Disk Subsystem with optical shield assembly that includes deployment critical features demonstrates repeatable deployment accuracy consistent with a total pre-launch petal position accuracy within ± 300 μm

- Petal position accuracy errors applied at the petal attachment hinges

Error component	**Allocation (μm)**
Radial bias	35
Radial random	150
Tangential random	120

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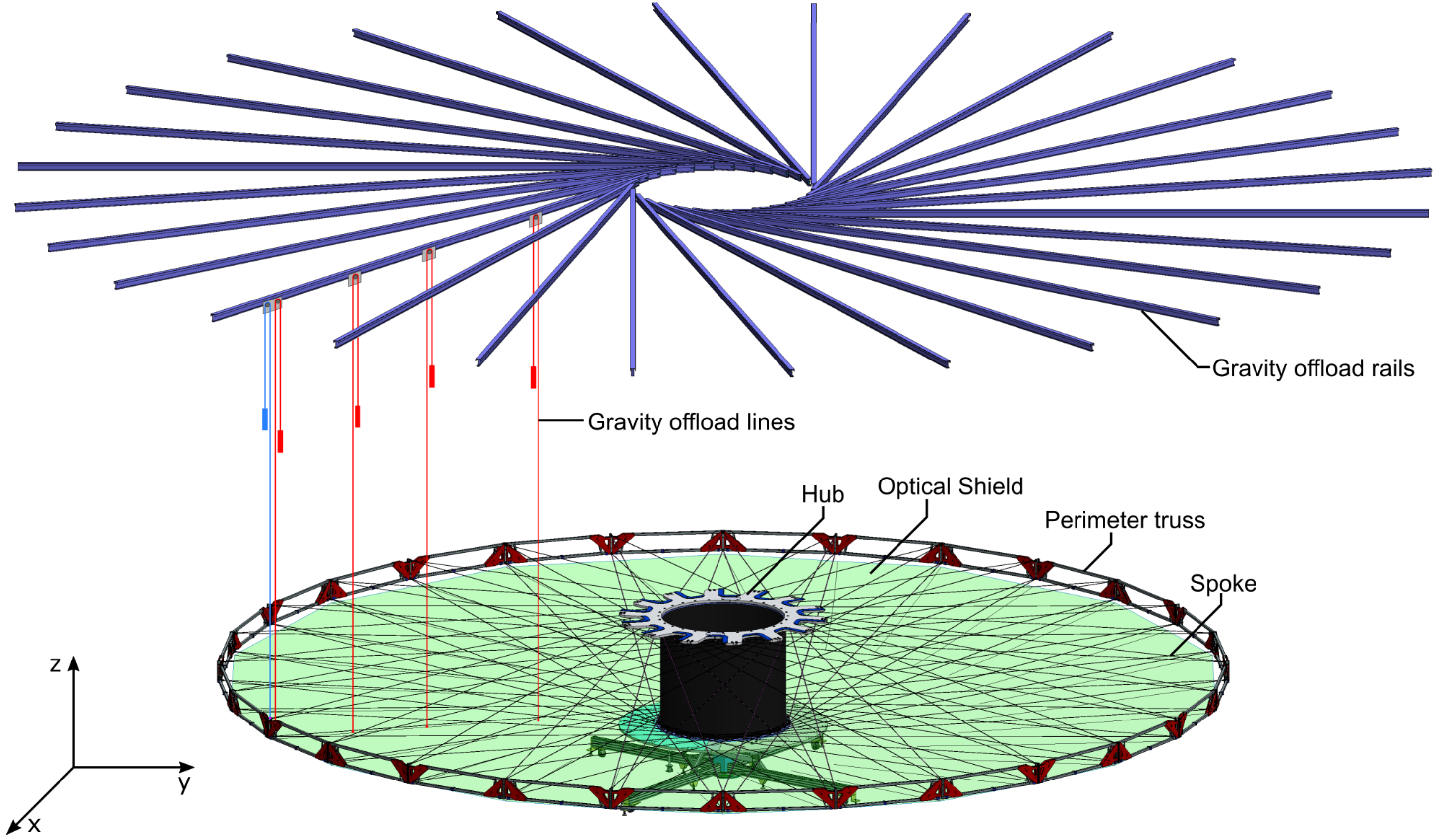
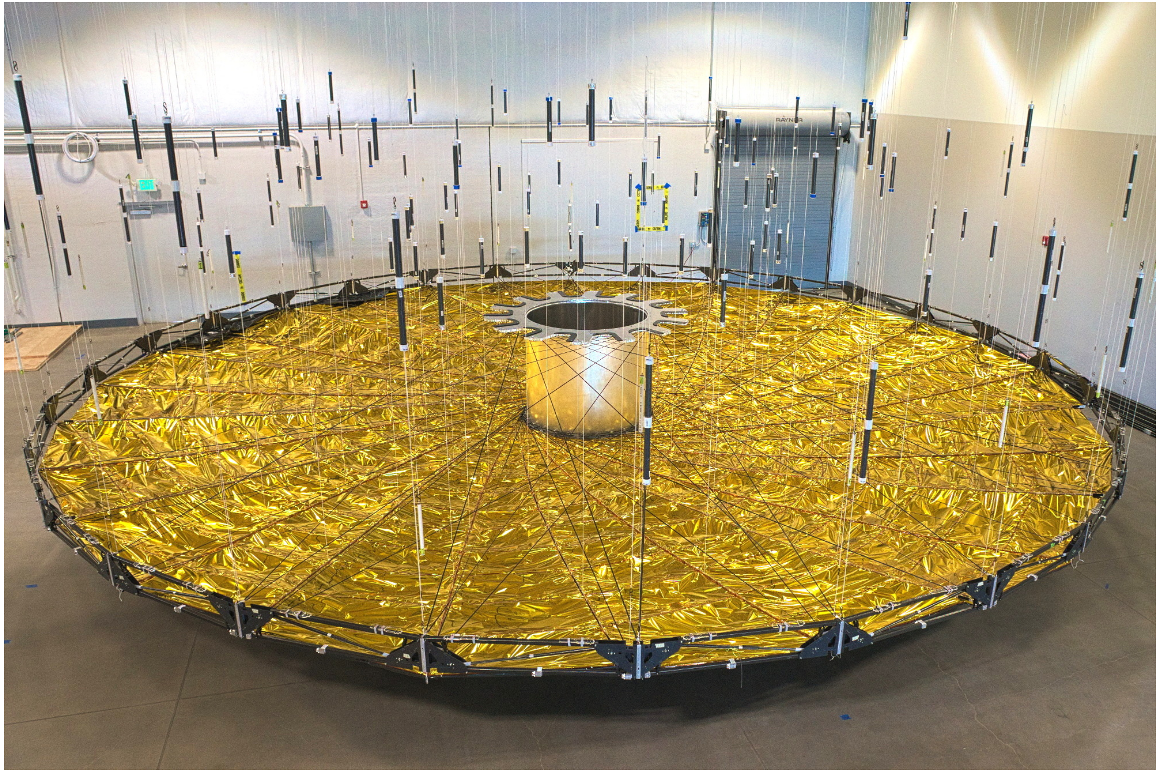
Experimental Apparatus



IDS Prototype



Deployed

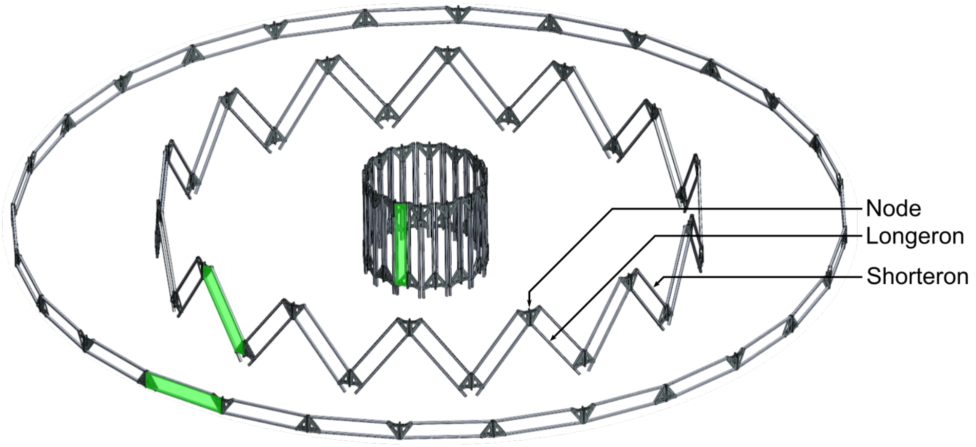
Stowed

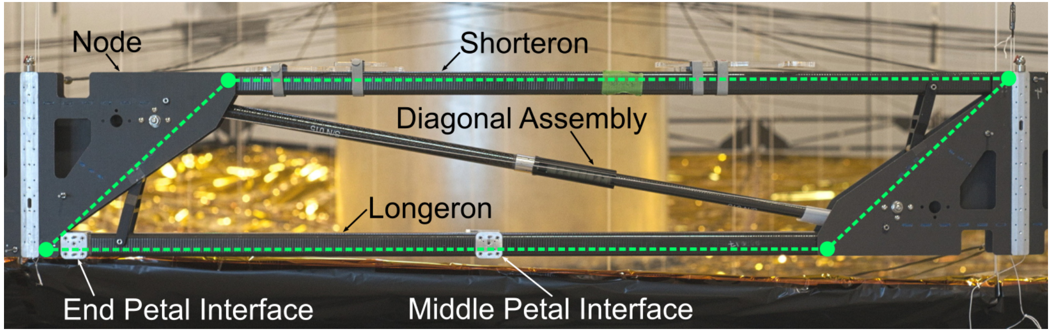
IDS Prototype Comparison to SRM Concept

	IDS Prototype	SRM IDS
Deployed IDS diameter	10.6 m	9.8 m
Stowed IDS diameter	2.3 m	2.3 m
Stowed IDS height	1.2 m	1.4 m
Central cylinder diameter	1.3 m	1.6 m
Number of petals	28	24

Perimeter Truss

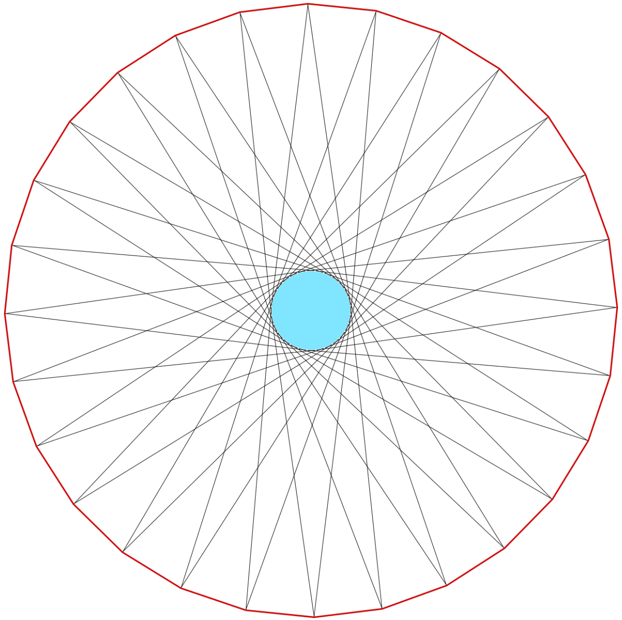
- Stowed barrel form → deployed ring
- 4-bar linkage of each truss bay enables stowage and deployment
- Driven by a single cable, routed along the diagonals of all bays
    - Cable gets reeled by a drive node
- Longerons and shorterons: CFRP with epoxy resin
- Nodes: CFRP plates bonded to aluminum center beam using epoxy

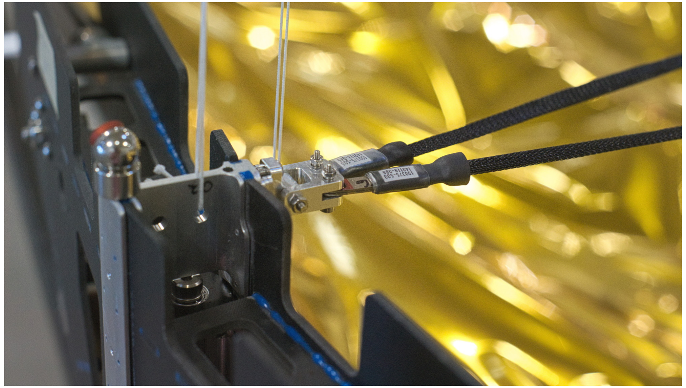




Spokes

- 4x 5.m-long spokes per node, 112 total
- Pulled into tension when deployed
- Provide a uniform tension field within the IDS for stiffness and precision
- Nominal spoke preload: 71 N (16 lbf)
- Comprised of unidirectional CFRP tape 6.35 mm wide, 0.10 mm thick
    - CFRP: IM7 carbon fiber in a PEKK matrix
    - Metal end-tabs bonded to CFRP tape using are bonded using PEI resin
    - Protected by flexible braided PEEK sheath
- Manufactured in custom precision jig; standard deviation of prestressed length: 54 µm

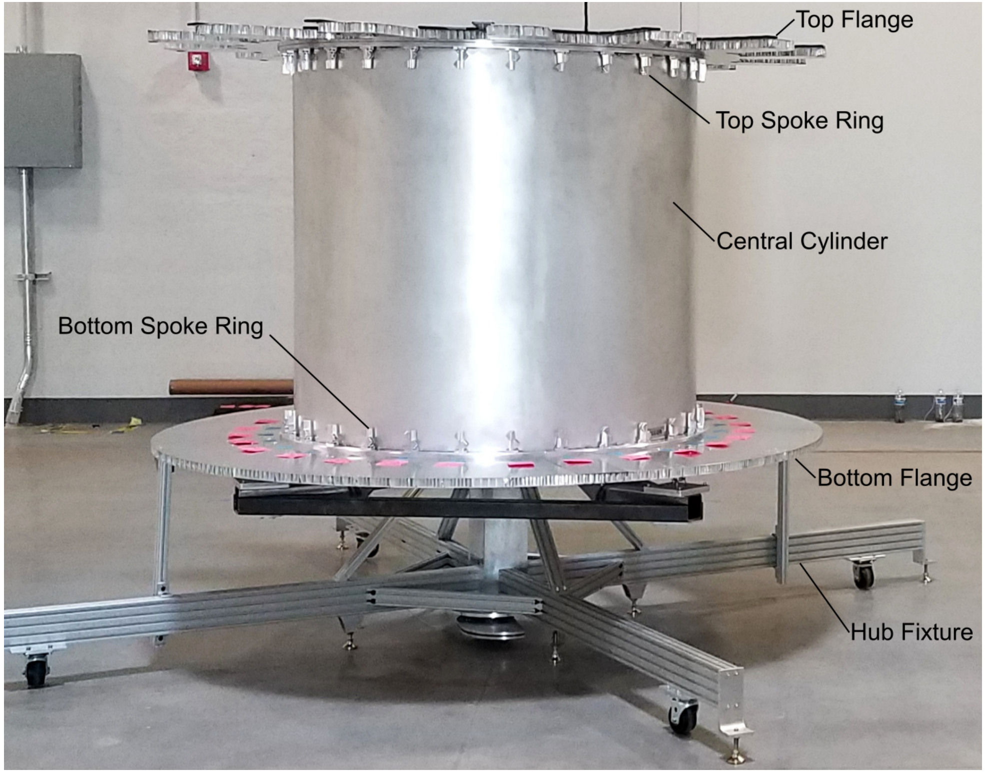




Hub

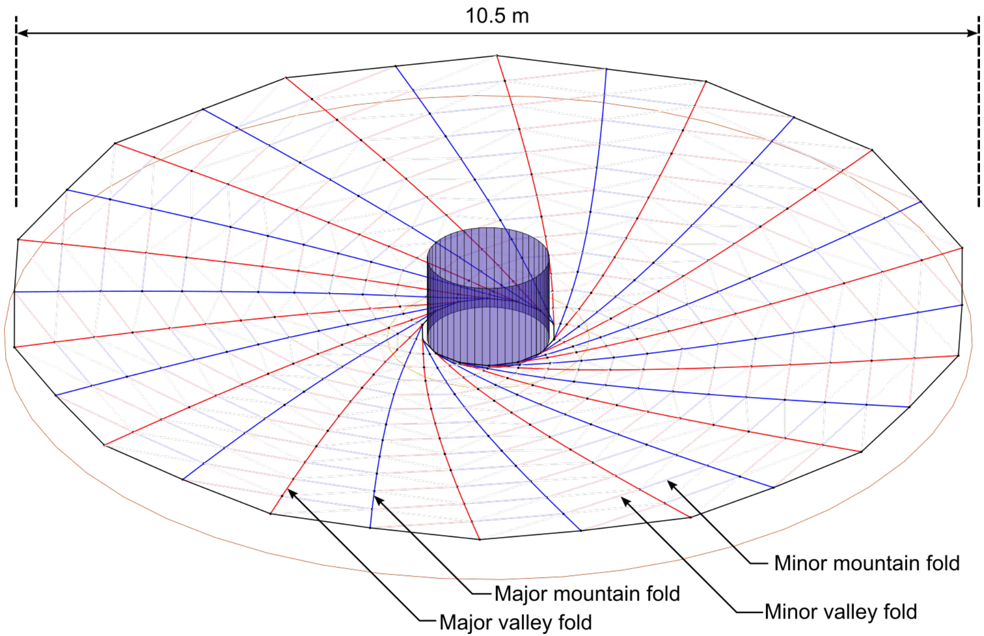
- Aluminum components bonded together:
  - 2x spoke rings
  - 1x central cylinder
  - 2x flanges

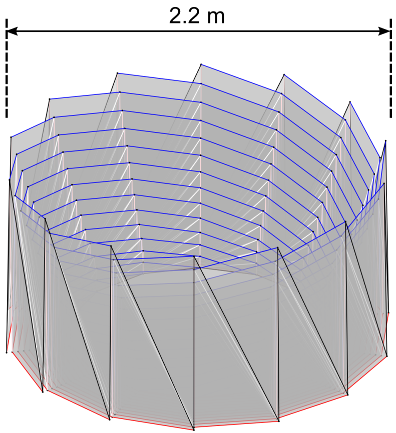
- Spoke interfaces on the hub were shimmed after complete assembly
  - Assuming a perfect truss, the residual shimming errors would result in spoke length errors of ±200μm



Optical Shield (OS)

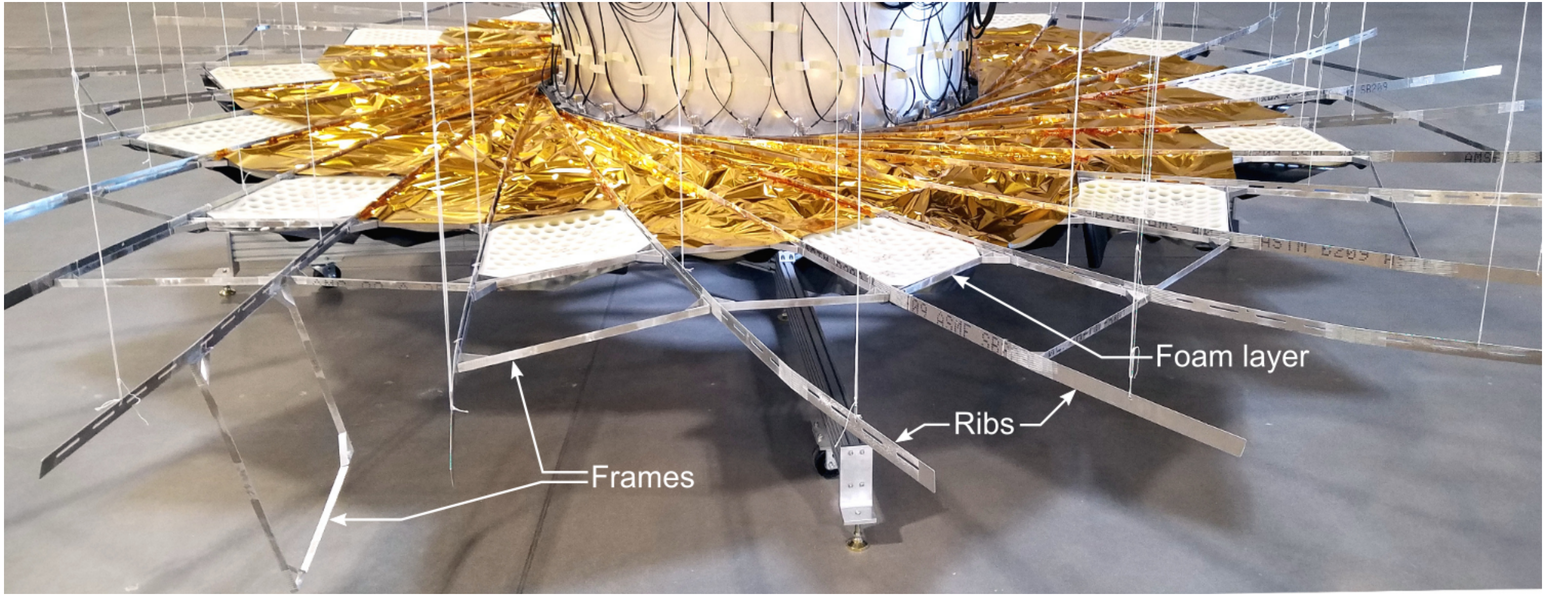
- Primary light-block element of the IDS
- Planar panels hinges together with revolute joints
    - Hinge placement (fold pattern) designed using modified origami algorithm
    - Deployed conical surface wraps while accounting for material thickess





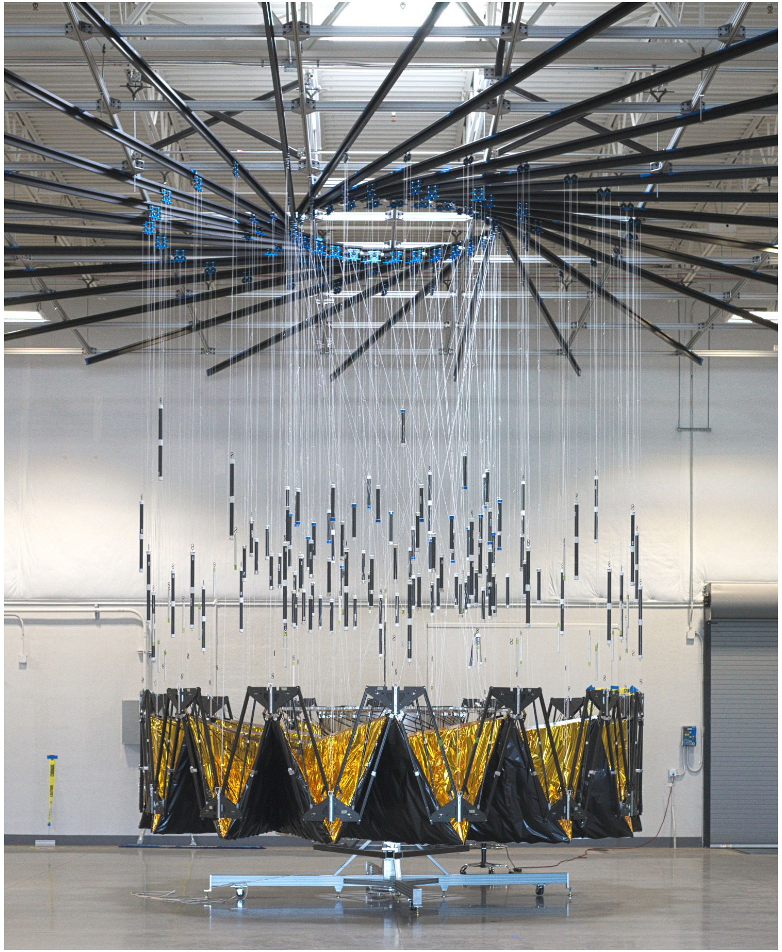
Optical Shield (OS)

- Planar panels made from aluminum “picture frame”
- Frame is filled with an opaque blanket made from 2x Kapton layers and a 16 mm-thick polyurethane foam layer
- 32 mm-tall foldable aluminum ribs along major fold lines for out-of-plane bending stiffness
- Out-of-plane bending stiffness is important for offloading, decoupling the OS from truss



Gravity Compensation

- Counterweighted at 140 discrete locations
  - 4 offload points at each major fold line
  - 1 offload point at each perimeter truss node
- Counterweight pulleys on wheeled carts, free to move along 28 overhead rails
  - ~5 m above the perimeter truss (when deployed)
- Structural hub held by a fixture
  - x, y, z translational degrees of freedom fixed
  - Rotation about the x, y axes fixed
  - Rotation about z-axis free; the hub needs to rotate relative to the perimeter truss during deployment as the OS is unwrapped

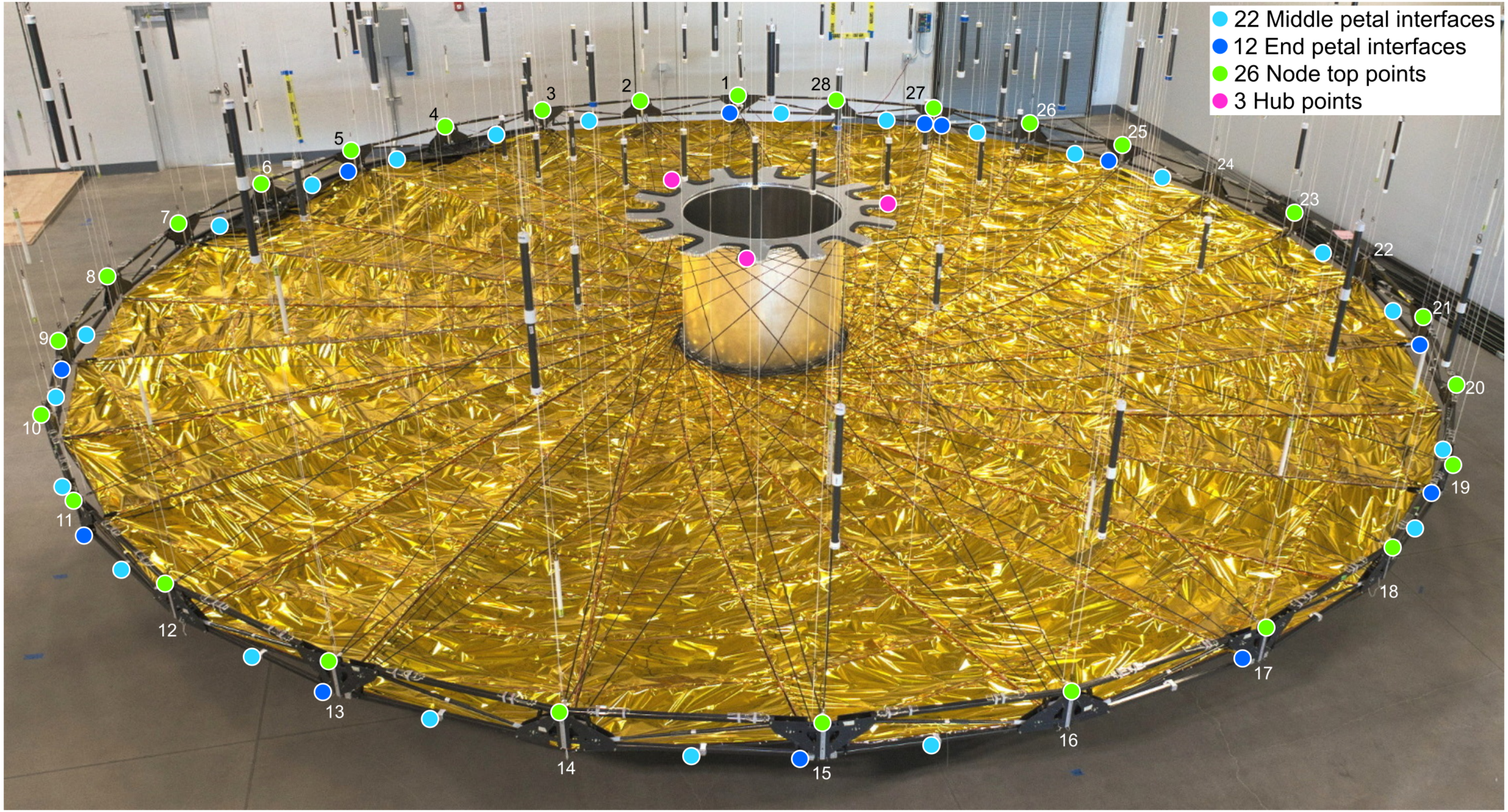


Metrology

- Leica AT402 laser tracker used to measure the 3D location of the centers of spherically mounted retroreflectors (SMRs) affixed to the IDS prototype
  - Maximum permissible error ±(15 μm + 6 μm/m of measurement range)
  - In practice, the laser-tracker-reported 3σ uncertainty was approximately half the maximum permissible error for the same range

- 67 SMRs visible to the laser tracker
  - 22 SMRs attached to the middle petal interfaces on the truss longerons
  - 12 SMRs attached to the end petal interfaces on the longerons
  - 26 SMRs on the tops of the node
  - 3 SMRs on the hub
  - 4 SMRs fixed to the floors and the walls as reference markers

SMR locations



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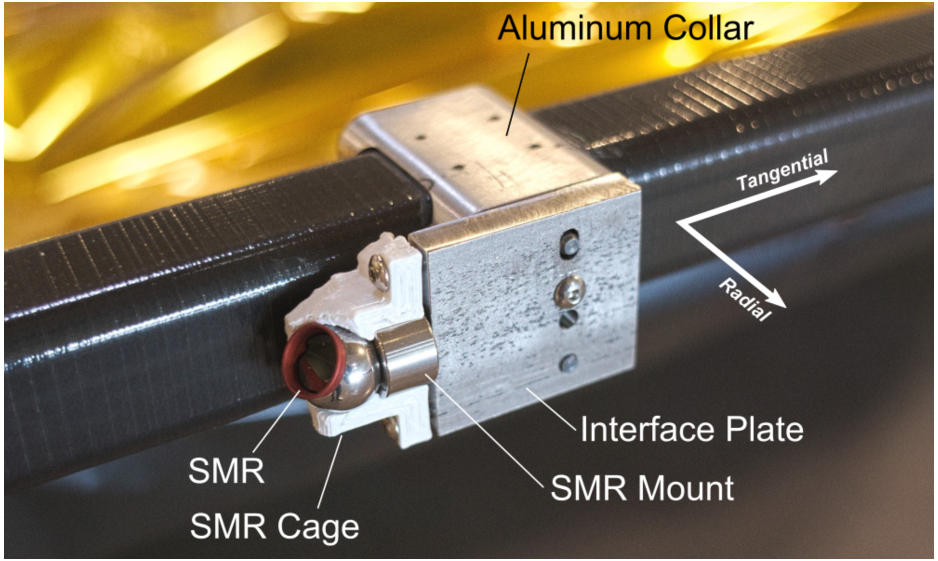
Shimming

- 8 rounds of measurement and shim adjustment were performed
  - For each round of measurement, at least 3 partial deployments were conducted, establishing a mean deployed position for each petal interface SMR
  - Based on these measured deployed locations, shim corrections were computed and implemented
  - Each petal interface SMR was shimmed to reduce deviation between measured location and a nominal design location

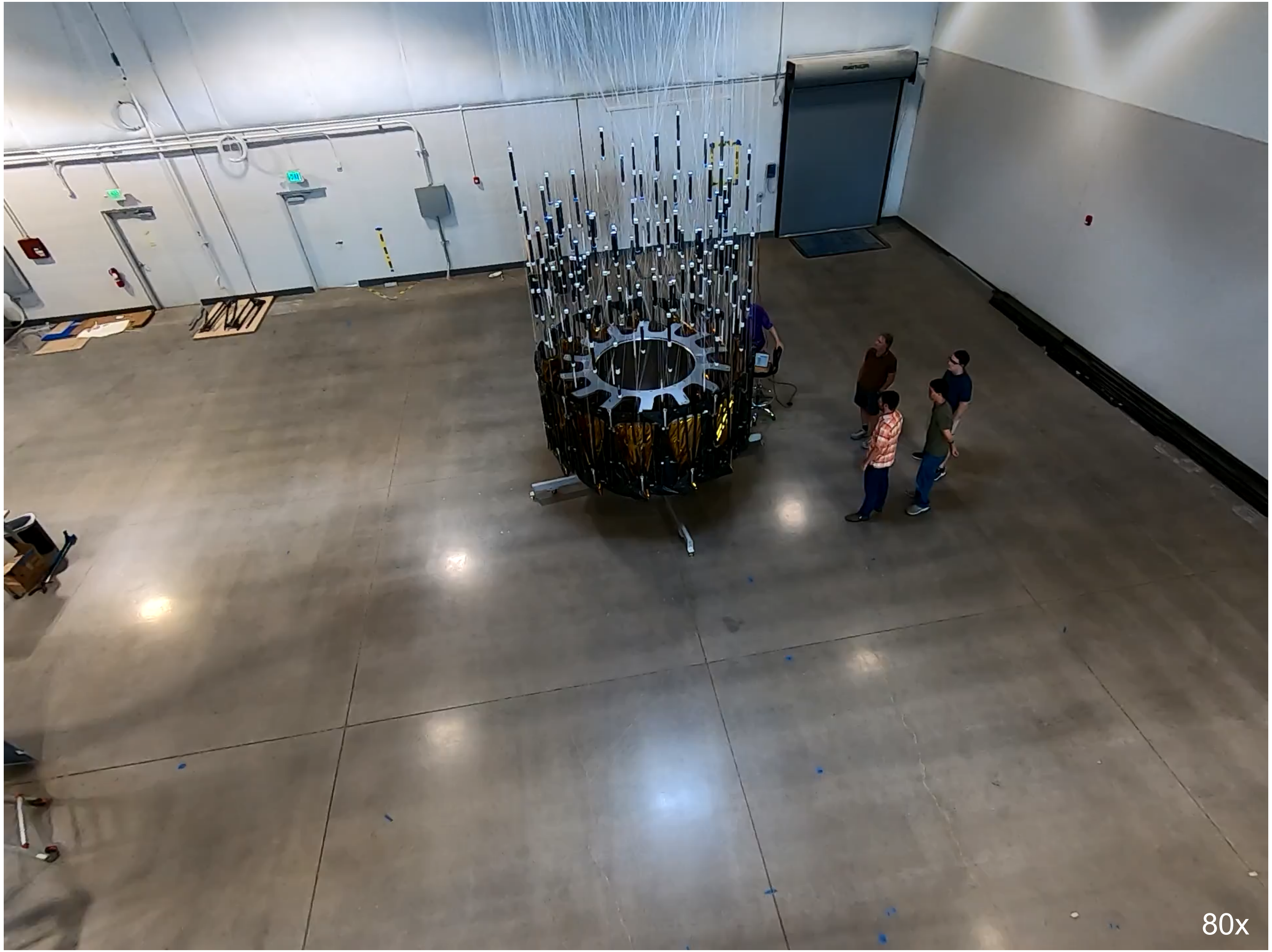


Stowage and Deployment

- 22 deployments performed at the final shim state
  - 5x from a 96% stowed state
  - 3x from a 82% stowed state
  - 3x from a 49% stowed state
  - 11x from a 8% stowed state

- Stow percent is defined as the angle between the longerons when stowed, divided by 180°, which is the angle between the longerons when fully stowed
  - Stow % = 100% is fully stowed
  - Stow % = 0% is fully deployed

	Timestamp	Stow %
1	2019.07.17	8
2	2019.07.17	8
3	2019.07.17	8
4	2019.07.17	8
5	2019.07.18	8
6	2019.07.18	82
7	2019.07.22	8
8	2019.07.22	8
9	2019.07.22	8
10	2019.07.22	8
11	2019.07.23	8
12	2019.07.24	82
13	2019.07.25	82
14	2019.07.25	49
15	2019.07.26	49
16	2019.07.29	49
17	2019.08.08	8
18	2019.08.12	96
19	2019.08.15	96
20	2019.08.16	96
21	2019.08.20	96
22	2019.08.21	96



https://exoplanets.nasa.gov/resources/2218/10m-starshade-inner-disk-deployment/

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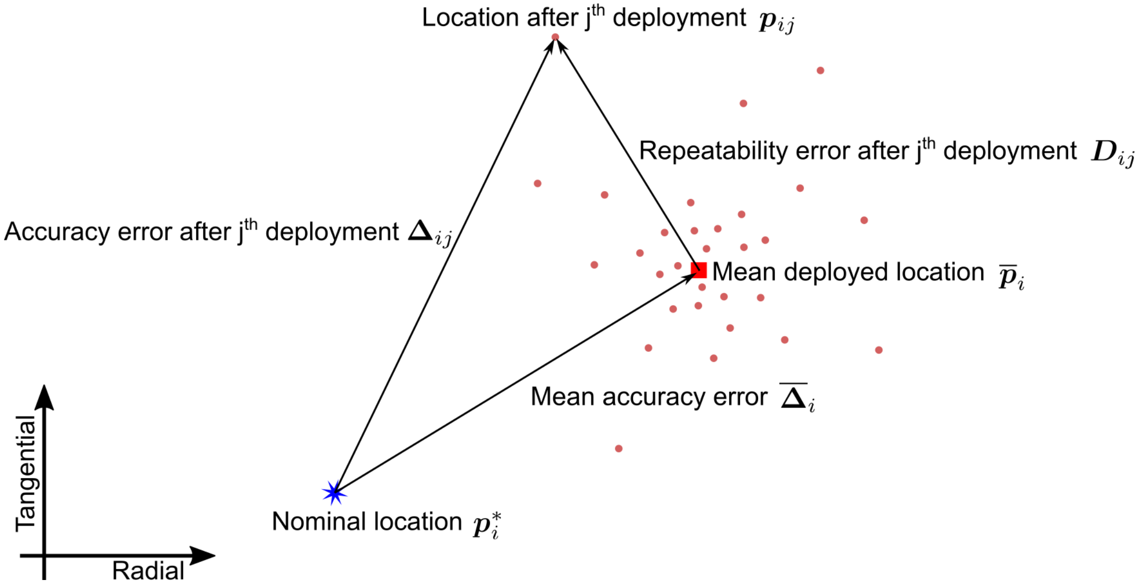
Data Processing

- At the end of each deployment, the location of the SMRs was measured, by an automated program
- Automated program was run 3 times at the end of each deployment, thus taking 3 independent passes
- The canonical deployed location of each SMR was taken to be the mean of the measurements from the 3 passes
- All SMR locations after a deployment were translated and rotated as a rigid body to best fit (in a least squares sense) the measured petal interface locations to the nominal petal interface locations

Definition of Deployment Errors

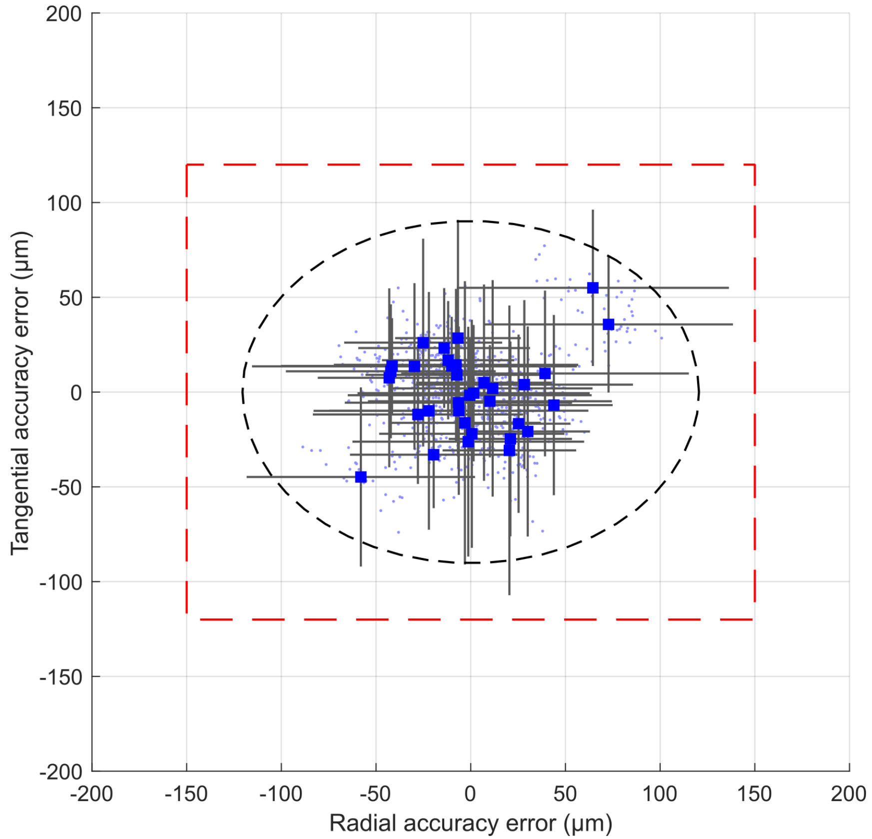
- Accuracy: deviation between the measured locations and the nominal location
  - Includes secular shape bias (shimming errors) that does not change between deployments
- Repeatability: deviation between the measured locations and the mean deployed location over all deployments
  - Measure of random variation from deployment to deployment of the system



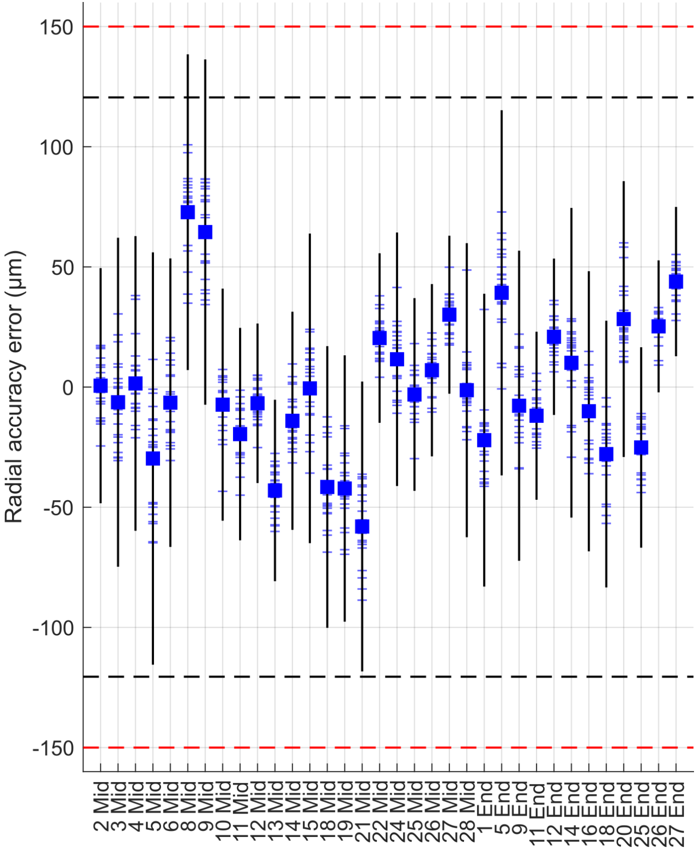
Tolerance Intervals

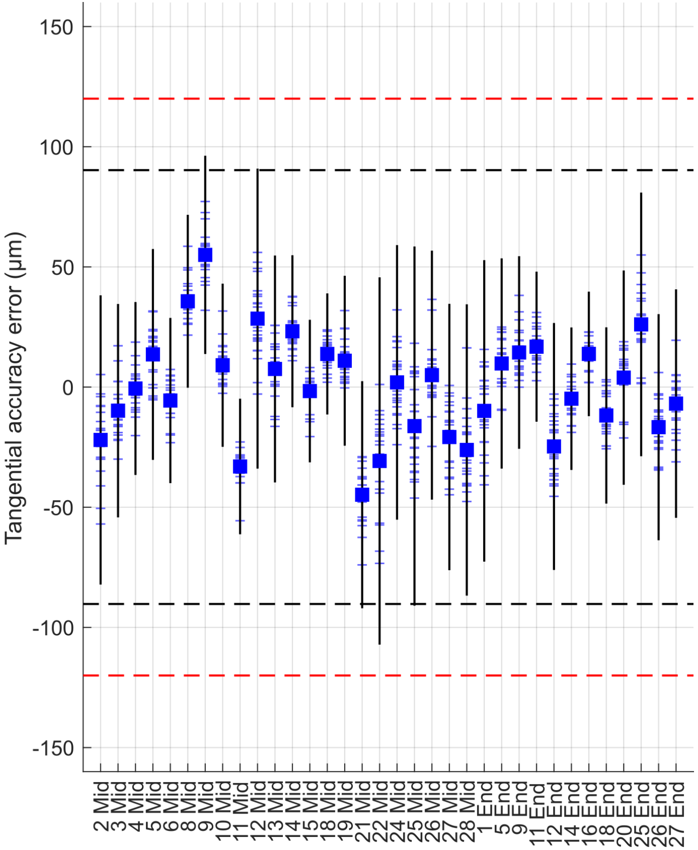
- We compute the standard deviations of the radial and tangential components of the accuracy and repeatability errors
- Given the low sample size – 22 deployments in total – the standard deviations of the sample may differ greatly from the standard deviations of the underlying population
  - To retire this uncertainty, tolerance intervals are employed
- A tolerance interval is a $\pm k\sigma$ region centered around the mean that will contain a percentage γ of future members of a population with a confidence level defined by $(1-\alpha)$; we use
  - $\gamma = 0.9973$
  - $(1-\alpha) = 0.90$
- For a sample size of 22 deployments, we get a tolerance interval of $\pm 3.8596\sigma$
  - Compare to a well-sampled normal distribution, for which 99.73% of the population falls within $\pm 3\sigma$

Accuracy Errors at Petal Interfaces

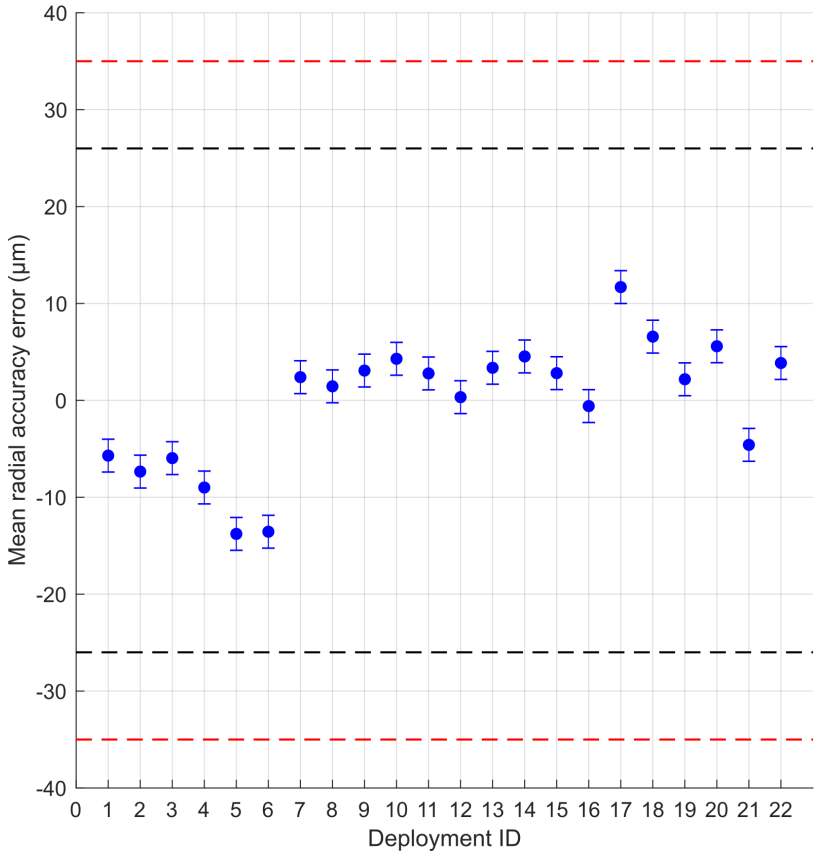


Accuracy Errors at Petal Interfaces

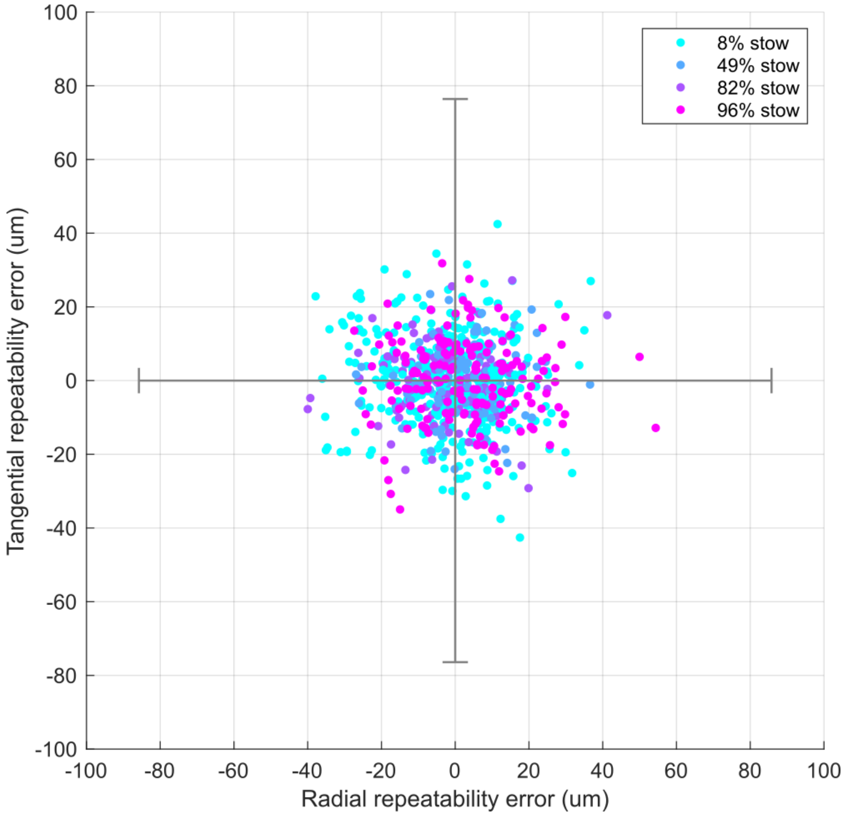




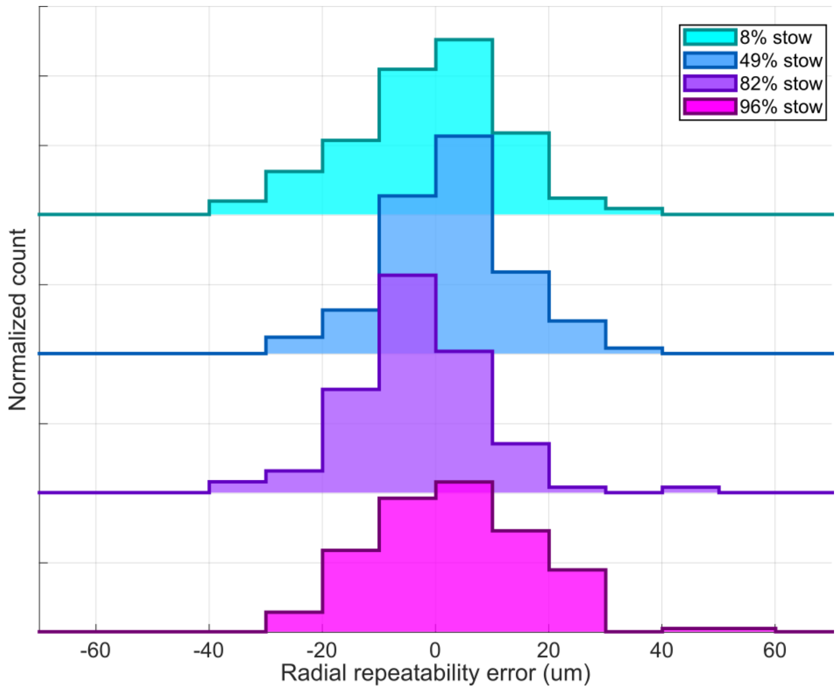
Accuracy Errors at Petal Interfaces

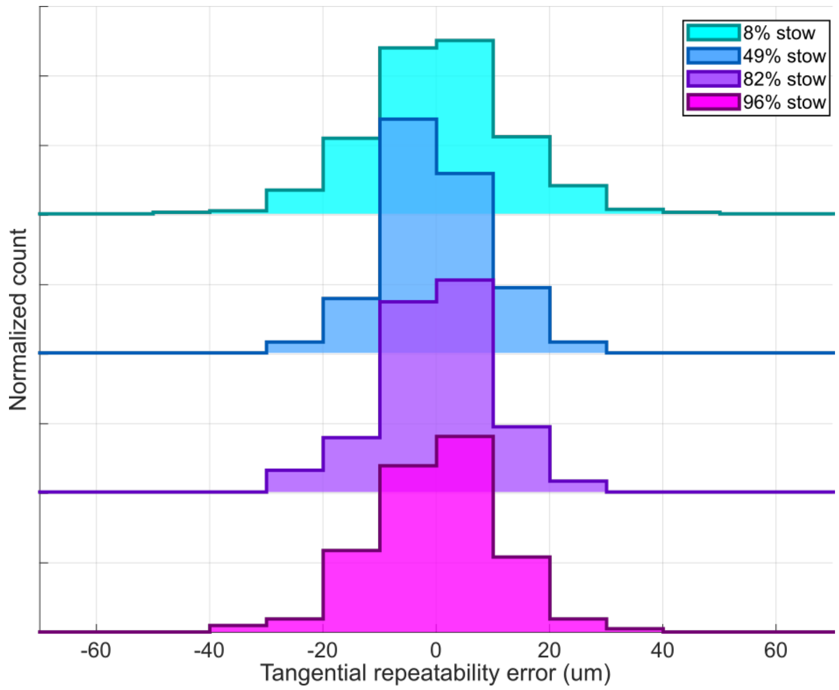


Repeatability Errors at Petal Interfaces



Validity of Partial Stows





Conclusions

- IDS prototype was deployed 22 times and the locations of 34 petal interfaces on the IDS were measured after each deployment
  - Tolerance intervals were calculated that would contain 99.73% of future deployment accuracy errors with 90% confidence
- All tolerance intervals were found to be within a 167 μm-radius circle
  - This meets the ± 300 μm requirement set out in Milestone 7C, with 44% margin
- In-plane deployment repeatability of the petal interfaces errors fell within a 86 μm-radius circle
  - Repeatability errors neglect shimming errors, which can be reduced in future efforts
  - Repeatability errors represent the ultimate deployment accuracy capability of the IDS

- It was demonstrated that the required IDS deployment accuracy is achievable with an integrated optical shield

Acknowledgments

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